ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUA4C1

# RECENT PROGRESS IN LOSS CONTROL FOR THE ISIS HIGH-INTENSITY RCS: GEODETIC MODELLING, TUNE CONTROL AND OPTIMISATION

H. Rafique*, E. K. Bansal, H. V. Cavanagh, C. M. Warsop
ISIS Neutron and Muon Source, RAL, Chilton, UK

*Abstract*

ISIS operates a high intensity 50 Hz rapid cycling synchrotron (RCS), accelerating up to $3 \times 10^{13}$ protons from 70 to 800 MeV. Protons are delivered to one muon and two neutron targets over two target stations, totalling 0.2 MW of beam power, enabling around 1000 experiments for approximately 3500 users a year. Minimisation of beam loss and optimisation of its control are central to achieving the best facility performance with minimal machine activation. We summarise recent work aimed at improving loss control in the RCS. Using geodetic survey data we aim to develop lattice models with realistic magnet alignment errors. Building on recent measurement campaigns a new and improved system of tune control has been developed and verified using updated lattice models in cpymad. More rigorous and quantitative measures of beam loss are being developed in order to optimise loss control.

## INTRODUCTION

The ISIS RCS is loss-limited: beam induced activation has to be controlled to allow hands on maintenance. The ISIS facility operates multiple user cycles a year, each necessitating periods of machine setup, with regular maintenance and upgrades performed in the short shutdowns between. Therefore, activation must be kept at levels such that hands-on maintenance may be performed shortly after the end of a user cycle.

The RCS, 163 m in circumference, accelerates up to $3 \times 10^{13}$ protons from 70 to 800 MeV at 50 Hz, in a 10 ms machine cycle. The RCS consists of 10 super-periods (SPs), each containing a combined function main dipole, a main quadrupole doublet, trim quadrupole doublet, and main quadrupole singlet, as illustrated in Fig. 1.

This paper describes historical loss control in the RCS, relevant issues identified after a long shutdown in 2021, solutions and long-term plans for performance optimisation learned from this experience.

### A Brief History of ISIS Operations

Reduction of beam loss is a perpetual goal in a loss-limited machine such as the RCS. ISIS has operated since 1995 with <12 % beam loss, <7 % in the early 2000s and <3 % by 2019 [1]. RCS beam loss and intensity since 2016 is summarised in Fig. 2.

Linac tank 4 was replaced during a long shutdown in 2021, due to ongoing issues and difficulty in maintenance

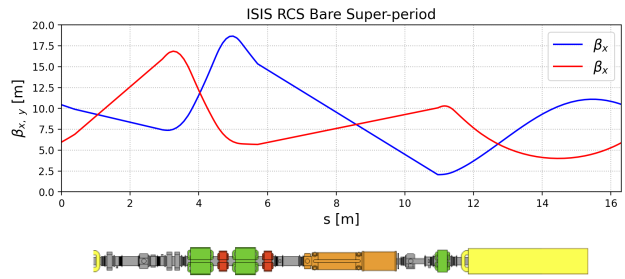


Figure 1: Top: Beta functions for design ISIS RCS superperiod. Bottom: Diagram of ISIS superperiod general layout. Quadrupole doublet (green), trim quadrupoles (red), RF cavity (orange), defocussing quadrupole singlet (green), combined function dipole (yellow).

due to age [2]. Alongside this, multiple upgrade and maintenance projects took place including significant upgrades to the second harmonic RF systems. The target, reflector and moderator assembly for target station 1 were also replaced, and is still in commissioning for high intensity operations. Since the 2021 long shutdown, operational issues have been identified and resolved, whilst others remain the focus of investigation.

### R&D Aims

ISIS accelerator physics R&D aims [3] include the development of more robust lattice models for operational understanding, and a focus on a more measurement-based setup.

In order to identify issues, a campaign of regular beam-based lattice measurements was instigated, including; investigations of the closed orbit, tune control, and optimisation of beam loss data. The aim of this work is to optimise the use of existing diagnostics and data, and to build on existing tools to better identify and further protect from issues. Such optimisation should result in reduced activation, by extension enhanced machine and personnel protection, as well as maximised equipment lifetime.

## ORBIT CONTROL

In the user cycles after the 2021 shutdown, operational issues were identified and rectified, some of which fall under human error, such as incorrect cabling and aperture restrictions. Once more easily rectifiable issues were corrected, underlying issues were identified such as larger than expected losses were observed in SPs 8 and 9, shown in Fig. 3.

* haroon.rafique@stfc.ac.uk

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUA4C1

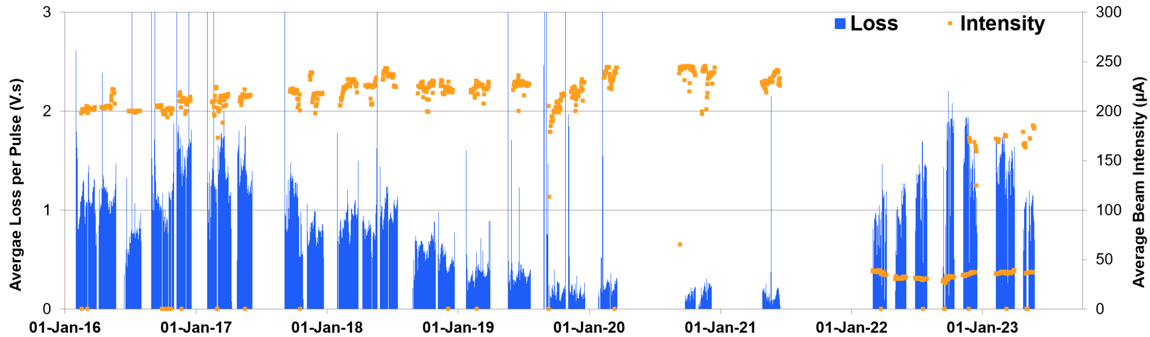


Figure 2: Average beam loss per pulse (blue) and average beam intensity (orange) in the ISIS RCS 2016–2023. Note, 10 Hz operation in 2022 due to target station 1 commissioning delays.

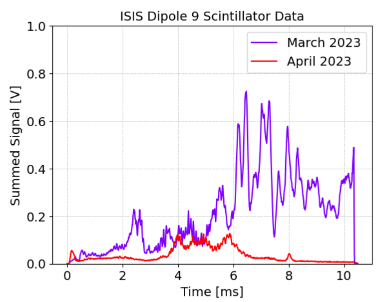


Figure 3: Dipole scintillators inside D9 indicating loss before and after magnet realignment.

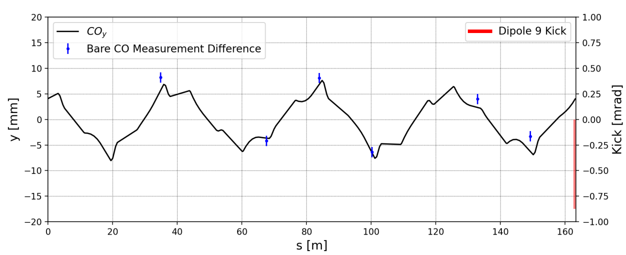


Figure 4: Measured bare closed orbit difference between 2014–2022 (blue), with predicted kick (red) and closed orbit (black).

The ninth main ring dipole (D9) was replaced in the long shutdown and was determined as the likely source of the beam loss. Operational investigation confirmed this, the magnet was realigned and losses reduced as a result.

Historical bare closed orbits were investigated in parallel, in an attempt to identify areas of concern. Comparing bare closed orbits from 2014 with 2022 a difference was obtained. Using cpymad [4] based ISIS RCS lattice models, thin kickers were introduced at each element, and matching procedures developed such that any closed orbit distortion or difference may be matched to the N most likely kicks. Using this algorithm, a single kick was identified in D9, as shown in Fig. 4.

This method is an approximation as it assumes thin kicks for long magnets. The next step was to properly apply the error to the MAD-X [5] element in the RCS lattice model. The ISIS main dipoles and doublet quadrupoles are regularly

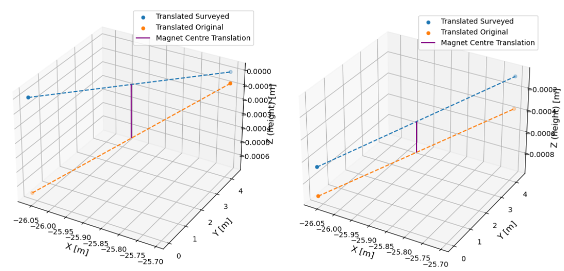


Figure 5: Left: Design survey vector (blue), January 2023 survey vector (orange). Right: January 2023 survey vector (blue), March 2023 survey vector (orange). Vector centre translations (purple) are equivalent to MAD-X magnet centre translations. All vectors shown are translated to be at magnet aperture centre rather than at survey targets.

surveyed in short shutdowns. As these measurements provide the physical misalignment information, a project was started to use geodetic survey and schematic data to infer magnet misalignments in the lattice.

### *Geodetic Survey Modelling*

Applying realistic misalignments to magnets based on survey data should improve the efficacy of lattice based tools such as the Closed Orbit Correction Utility. Additional to this, a tool that can infer the bare closed orbit from magnet survey data would provide the means to request in-situ realignment.

Using survey data, two points per magnet, an alignment vector is generated. The original alignment vector is assumed to correspond at the centre of the MAD-X described lattice magnet. Preliminary data is promising, as shown in Fig. 5, D9 survey data shows a misalignment with respect to the original design position as identified. The right hand plot shows the difference between subsequent surveys in 2023.

Survey data is supported with available, original design drawings. Currently the original design positions of the main dipoles are known. The original design positions of the main quadrupoles may be inferred after further measurements which are planned at the time of writing. After consideration of systematic errors, a misalignment vector may be defined for each magnet using such data.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUA4C1

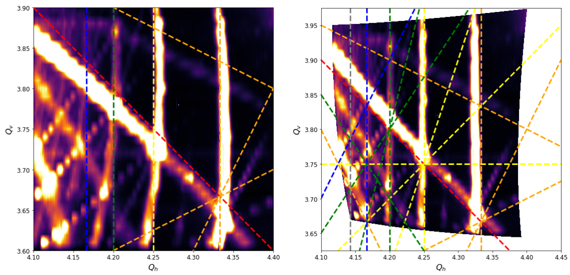

Figure 6: Dynamic tune scans; $Q_x$ is kept constant whilst $Q_y$ is scanned down, indicating increased loss with brightness. Left: Raw data. Right: Tune control corrected data. Note the operational tune area is unaffected.

Comparing the misalignment vector with the MAD-X segmented magnet description, the translation indicated by the purple line in Fig. 5 provides the co-ordinate transform at magnet centre. From this position one may use standard MAD definitions and basic geometry to define the values of the 6 MAD-X EALIGN parameters; $\Delta s$, $\Delta x$, $\Delta y$, $\Delta\Psi$, $\Delta\Phi$, $\Delta\Theta$ at each segmented element start.

Dedicated measurements are planned to verify the efficacy of this approach with bare closed orbit data. With regularly performed measurements, this should produce more effective models for operational tools and investigations, as well as identify out-of-tolerance alignments prompting magnet re-alignment before establishing vacuum. This process should result in improved bare closed orbit prediction and control.

## TUNE CONTROL

The ISIS RCS tune control is based on the analytical approximation of the change in tune from bare lattice design tunes $(Q_x,Q_y)_{\text{bare}}$ = (4.331, 3.731), due to a quadrupole change $\left(dQ = \frac{1}{4\pi}\int \beta(s)\, dK(s)\, ds\right)$ [6]. Resonance identification studies using dynamic tune scans [7] show curvature in resonance lines. As shown in Fig 6, this curvature is due to the tune control method.

To investigate this curvature, the error in tune control method may be calculated analytically. By inserting the normal quadrupole coefficient $K$, as calculated by the tune control approximation, into the full lattice model, one may define a difference between requested and expected values. The resulting absolute sum of the $(Q_x, Q_y)$ errors is shown in the left plot in Fig. 7. It is noted that operational working points fall within the area of lowest error, as consistent with theory and historical operation.

### *New Tune Control*

An updated tune control, allowing simple implementation in the control system without a full lattice model, originally developed by P. T. Griffin-Hicks, defines the two trim quadrupoles per SP as matrices $(\bar{M}_{QTF}, \bar{M}_{QTD})$. By calculating the transfer matrices between the trim quadrupoles $\bar{A}$ and $\bar{B}$, one may construct a simple SP:

$$\bar{M}_{SP} = \bar{M}_{QTD} \cdot \bar{A} \cdot \bar{M}_{QTF} \cdot \bar{B}.$$

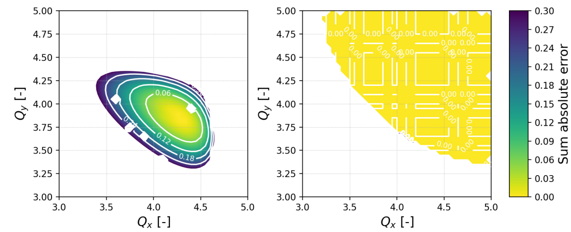

Figure 7: Contours indicating error in original tune control. Set vs predicted tune using original tune control (left) or new tune control (right) to calculate $K_{(QTD,QTF)}$.

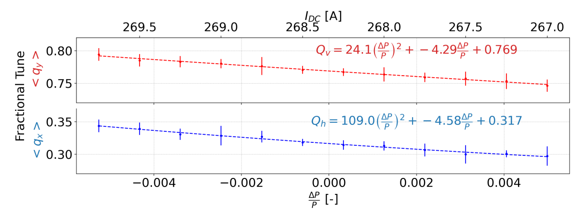

Figure 8: Chromaticity measurement taken September 2023.

The new tune control method takes into account changes of lattice parameters with tune. Thus we may arbitrarily modify a lattice model to agree with measurements, and analytically recalculate the best available tune control. The predicted error from the new tune control is a significant improvement on the existing control, over a wider tune range, as shown in the right plot in Fig. 7. The new tune control is currently being implemented, for verification the chopped beam measurement is utilised.

### *Chopped Beam Measurements*

Operating the RCS in storage ring mode, with only DC power to main magnets, and RF cavities detuned and powered down, the beam energy remains constant at 70 MeV. A beam chopper in the injection line allows a short pulse of ~600 ns to be injected. This small transverse emittance, chopped beam pulse behaves similarly to a single particle [6], and its natural oscillation can be observed as it decoheres over ~50 turns using beam position monitors (BPMs) distributed around the RCS. Seven parameters are extracted from the least-squares fit of this oscillation for each BPM, including the tune, with an error of ± 0.004 [6].

Repeating measurements as a function of scaling main magnet field gives chromaticity. The chromaticity is observed as $\xi_x$ = -1.061= ± 0.1 and $\xi_y$ = -1.14 ± 0.11, as shown in Fig. 8. The bare lattice tunes are also extracted $(Q_x, Q_y)$ = (4.317, 3.769), which is consistent between 2018 - 2023.

This measurement provides a rigorous low intensity tune verification method. Regularly performed these measurements feed back into the latest lattice model, which scales quadrupole fields to obtain the measured bare tune. To match the measured bare tune of $(Q_x, Q_y)$ = (4.317, 3.769), doublet quadrupoles are reduced in strength by 1.1 % and 1.4 %, and singlet quadrupoles reduced by 0.7 %, compared to historic reference data. It is noted that despite multiple magnet

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUA4C1

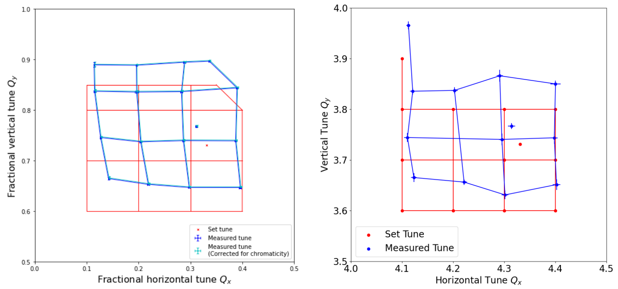


Figure 9: Q grid measurement taken 2019 (left) and 2023 (right).

measurement campaigns, accurate data is not available for all installed magnets.

Measuring tune in an orthogonal grid, as compared in Fig. 9, we may observe the limitations on current tune control methods. Post 2021 shutdown the measurement indicates a larger error on each measurement, but similar displacement of the tune plane. This measurement provides a diagnostic for other faults, in this case thought to be jitter in ion source output. Despite this, it is evident that the bare lattice tunes are consistent, and the error around the bare lattice tune is similar before and after the 2021 shutdown.

The new tune control is currently being implemented and tested as part of the ISIS controls system upgrade [8]. Using chopped beam measurements, the new tune control method will be carefully validated before being deployed operationally. Chopped beam measurements are regularly performed to provide lattice status metrics, and improve lattice models.

## OPTIMISATION OF LOSS DATA

ISIS is loss limited by activation, thus monitoring of losses is vital to operation and regular maintenance. Thirty-nine 3-metre long argon filled ionisation chambers are located along the inside radius of the RCS, giving almost total coverage. These beam loss monitors (BLMs) are designed to detect the isotropically emitted evaporation neutrons generated in nuclear interactions between lost beam protons and the surrounding material [9]. As the large iron yoke of the 10 main dipoles shield the BLMs, each dipole contains 6 scintillators which provide additional loss monitoring [1]. Intensity toroids together with the sum of the 39 BLMs are used as key figures of merit.

Losses integrated over the machine cycle are interlocked for protection, and displayed in multiple applications. Trip levels are set using experience of induced activation. This system has worked robustly to minimise activation and allow regular maintenance for many years. Monitoring such large data sets, in the context of the 50 Hz energy ramp, can be difficult whilst tuning the machine. In order to support operation, systems for more efficient use of this data are being developed.

Intensity monitors are well calibrated to number of lost protons, but have limited sensitivity at ~0.1 %. BLMs are highly sensitive, dependent on energy, at ~0.01 % or better,

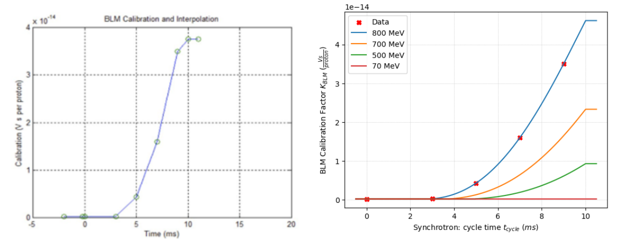


Figure 10: BLM calibration to protons (left) scaled to arbitrary extraction energy (right).

but lack detailed calibration to lost protons. Campaigns in 1993, 2003, and 2016 have induced losses at intervals in the 10 ms acceleration cycle and correlated the intensity monitor decrease with the integrated BLM sum. Performed at multiple times in the cycle a calibration curve may be established. Recent analysis has shown 2016 data to converge on the 2003 calibration curve shown on the left plot in Fig. 10. This is scaled with extraction energy on the right plot in Fig. 10.

Despite an intrinsic uncertainty in the calibration (depending on what the beam hits), a consistent calibration provides useful conversion from raw signal in volt-seconds, to number of protons, energy, or power lost. Using this data, better metrics of loss may be defined for operation. Low levels of loss may be analysed in detail through the acceleration cycle, and spatially.

Beam loss monitor data is digitised using LabVIEW [10] on PXIs, streamed via the MQTT protocol [11], and received via the python Eclipse Paho client [12]. This allows development of new operational tools such as loss quantification, temporal and spatial identification, and monitoring of loss over time. Long term storage of loss and intensity data will be used to reinforce the calibration. Future plans include detailed modelling of lost proton interactions with machine materials in order to reduce the calibration error, inform activation studies, and provide a deeper understanding of losses in the RCS.

## CONCLUSION

Closed orbit control has proven critical in recovering performance post 2021 shutdown, magnet survey data is being used to develop closed orbit predictions in order to protect against magnet misalignments. An improved tune control has been developed, and chopped beam measurements are regularly performed to obtain lattice parameters such as the bare tune and chromaticity, which are used to develop more representative models. Highly sensitive beam loss data has been calibrated to provide loss in protons, energy, or power. BLM data has been streamed to be python-accessible for new analysis tools which will support a rigorous understanding of losses and activation in the RCS. With respect to beam loss, operational figures of merit are being developed. Learning from issues identified post 2021 long shutdown, this work aims to provide protection against future operational difficulties, as well as support a measurement based machine setup.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-TUA4C1

## ACKNOWLEDGEMENTS

The authors are grateful to former ISIS staff, Peter Griffin-Hicks, for his work on tune control; the ISIS; Accelerator Physics group for fruitful discussion, Diagnostics group, Diagnostics Software section, Controls group, and Operations Crew for their invaluable support, Sara Karbassi for upgrading chopped beam analysis tools, the Survey section for their diligent measurements, and 26 work experience students for developing beam loss GUI prototypes.

## REFERENCES

[1] B. Jones, S. A. Fisher, and A. Pertica, "Beam loss control with scintillating monitors at ISIS", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 2701–2704. doi:10.18429/JACoW-IPAC2019-WEPGW091

[2] A. P. Letchford, "Upgrades and developments at the ISIS Linac", in *Proc. 31st Int. Linear Accelerator Conf. (LINAC'22)*, Liverpool, UK, Aug.-Sep. 2022, pp. 1–6. 10.18429/JACoW-LINAC2022-MO1AA01

[3] R. E. Williamson *et al.*, "High-intensity studies on the ISIS RCS and their impact on the design of ISIS-II", presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1I2, these proceedings.

[4] T. Gläßle, R. De Maria, Y. Levinsen, and K. Fuchsberger, "cpymad", v1.13.0, 2023. doi:10.5281/zenodo.7752353

[5] MAD-X project, https://cern.ch/madx

[6] C. M. Warsop, "Special diagnostic methods and beam loss control on high-intensity proton synchrotrons and storage rings", PhD thesis, Sheffield University, UK, 2002.

[7] P. T. Griffin-Hicks, B. Jones, B. G. Pine, C. M. Warsop, and M. Wright, "Experimental measurements of resonances near to the ISIS working point", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1132–1135. doi:10.18429/JACoW-IPAC2018-TUPAL054

[8] L. Fernandez-Hernando, "Transitioning to EPICS while involving users and operators", presented at the 13th Workshop on Accelerator Operations, Tsukuba, Japan, Sep. 2023. https://conference-indico.kek.jp/event/184/contributions/4402/attachments/2967/3966/OR08-FERNANDEZ-ISIS.pdf

[9] M. A. Clarke-Gayther, G. M. Allen, and A. I. Borden, "Global beam loss monitoring using long ionisation chambers at ISIS", in *Proc. 4th Eur. Particle Accelerator Conf. (EPAC'94)*, London, UK, Jun.-Jul. 1994, pp. 1634-1637.

[10] R. Bitter, T. Mohiuddin, and M. Nawrocki, *LabVIEW: Advanced programming techniques*, Boca Raton, FL, USA: CRC Press, 2006. https://doi.org/10.1201/9780849333255

[11] MQTT Version 5.0., Mar. 2019, https://docs.oasis-open.org/mqtt/mqtt/v5.0/mqtt-v5.0.html

[12] ECLIPSE Foundation Paho Client, https://git.eclipse.org/c/paho/